Renewable and Sustainable Energy Reviews 15 (2011) 3539–3551

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Biochar production potential in Ghana—A review

Moses Hensley Duku[a,b,c], Sai Gu[a,c,*], Essel Ben Hagan[b]

[a] School of Engineering Sciences, University of Southampton, Southampton S017 1BJ, UK
[b] Institute of Industrial Research, Council for Scientific and Industrial Research, P.O. Box LG 576, Legon, Ghana
[c] Xi'an Jiaotong-Liverpool University, No. 111 Ren'ai Road, Suzhou 215123, PR China

ARTICLE INFO

Article history:
Received 30 December 2010
Accepted 30 May 2011
Available online 18 July 2011

Keywords:
Biochar
Carbon sequestration
Agricultural crop residues
Soil fertility

ABSTRACT

Biochar is being promoted for its potential to improve soil properties, crop productivity and carbon sequestration in soil. Obstacles that may hinder rapid adoption of biochar production systems include technology and production costs, and feedstock availability. In this paper, a review of biochar production potential in Ghana is given. The availability of potential feedstock for biochar production such as agricultural residues, forestry residues, wood processing waste, the organic portion of municipal solid waste and livestock manure, together with a brief description of biomass conversion routes for biochar production is also given. Furthermore, potential agronomic and environmental benefits that can be derived from the application of biochar in soils are discussed. It is concluded that the large availability of biomass resources in Ghana gives a great potential for biochar production in the country.

Contents

* Corresponding author at: School of Engineering Sciences, University of Southampton, Southampton S017 1BJ, UK.
E-mail addresses: s.gu@soton.ac.uk, sai.gu@xjtlu.edu.cn (S. Gu).

1364-0321/$ – see front matter © 2011 Elsevier Ltd. All rights reserved.
doi:10.1016/j.rser.2011.05.010

1. Introduction

Application of biochar to soils is currently gaining considerable interest globally due to its potential to improve soil nutrient retention capacity, water holding capacity, and also to sustainably store carbon, thereby reducing greenhouse gas (GHG) emissions [1–5]. Enhanced nutrient retention and water holding capacity of soils reduces the total fertilizer requirements and environmental deterioration associated with fertilisers [6,7]. Biochar is a form of charcoal produced through the thermochemical process of biomass under low oxygen conditions known as pyrolysis. Various types of biomass such as agricultural crop residues, forestry residues, wood waste, organic portion of municipal solid waste (MSW) and animal manures have been proposed as feedstock for biochar production. However, the suitability of each type of biomass as feedstock is dependent on the nature, chemical composition, environmental, as well as economic and logistical factors [1]. Pyrolysis conditions for biochar production, together with feedstock characteristics largely control the physical and chemical properties (e.g. composition, particle and pore size distribution) of the resulting biochar, which determine the suitability for a given application [1]. Biochar is highly recalcitrant in soils, with reported residence times for wood biochar being in the range of 100s to 1000s of years, i.e. approximately 10–1000 times longer than residence times of most soil organic matter (SOM). Therefore, biochar addition to soils could provide a potential sink for carbon [1].

In sub-Saharan African (SSA) countries, the decline in soil fertility is attributed mainly to continuous cultivation, coupled with rapid organic matter mineralisation. Furthermore, the presence of highly weathered secondary minerals and high soil acidity has been identified as a major cause of food insecurity and poverty [8]. Soil erosion has also been recognised to have a direct negative effect on crop productivity which consequently has repercussions on the economy [9,10]. As a result of land degradation, irrigated lands in SSA countries are reported to average below 7% of their potential productivity. Rain-fed crop plants and rangelands are also reported to be 14% [8] and 45% [11] below their potential productivity respectively. In particular, agricultural systems in Ghana are characterized by low productivity, depending on low and erratic rainfall patterns, out-dated agricultural practices and low application of inputs. Most of the sandy loamy soils in the country are highly weathered and characterized by poor fertility as a result of high erosion rates. It is estimated that soil fertility loss through erosion could reduce agricultural income in the country by US$4.2 billion and could further cause a 5.4% increase in the poverty rate during the period 2006–2015 [10,11]. About 57% of the economically active population in Ghana is engaged in agricultural activities, mostly as smallholder subsistence food crop farmers who depend on these marginal soils for their livelihoods. Food production is mainly through the extensive system of shifting cultivation in which farmers “slash and burn” a piece of land, grow food crops in poly-culture for 1–3 years and leave it fallow. However, this type of agricultural practice causes rapid reduction in forest cover and land degradation. Although, the shifting cultivation system helps restore soil fertility, the progressive reduction in the fallow period as a result of increasing population pressure makes it unlikely for these soils to regain high fertility levels [11–13].

Current strategies adopted for agricultural intensification in Ghana include the use of chemical fertilizers and technological means. However, the potential of this type of intensification is limited due to its affordability and accessibility by smallholder-farmers. Consequently, the amount and efficiency of fertilizer use in the country is very small. The Integrated Soil Fertility Management option, which combines the application of both inorganic fertilizers and organic fertilizers for increased crop production rather has some associated problems. When applied, the decomposition of organic fertilisers releases GHGs such as carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) [6,11,12].

Global concerns for climate change, however, necessitate the search for and promotion of alternative agricultural management practices that can be employed to achieve food security and at the same time, contribute to climate change mitigation [6]. Such practices should also be capable of reducing poverty, meeting farmers' needs and minimizing the impact on environmental resources. Application of biochar to soils has been identified as a technology that can stabilize organic carbon and also reduce GHG emissions [14]. Despite this potential, there is, however, limited knowledge of potential feedstock available in Ghana, and also technologies available for the production of biochar.

The objective of this paper is to review the potential of biochar production in Ghana. It examines the availability of biomass resources, thermochemical biomass conversion processes, and potential agronomic and environmental benefits that can be derived from biochar application to soils.

2. Biomass resources in Ghana for biochar production

There are various types of biomass resources in Ghana, namely agricultural crop residues, agricultural by-products, forestry residues, wood waste, organic portion of municipal solid waste (MSW), industrial wastewater and manures. A comprehensive review of biomass resources and biofuels potential in Ghana has already been given [15]. Biomass is the major energy source in Ghana and contributes about 64% of the country's primary energy supply [15]. The significant abundance of lignocellulosic biomass globally makes it a potential feedstock for biochar production. Composed mainly of cellulose, hemicellulose, lignin, and small amounts of extractives, lignocellulosic biomass has an average elemental composition of $CH_{1.4}O_{0.6}$ [16]. The composition and proportions of these constituents vary with the type of biomass. The suitability of a particular biomass as a potential feedstock for biochar production depends upon various characteristics such as moisture content, calorific value, fixed carbon, oxygen, hydrogen, nitrogen, volatiles, ash content, and cellulose/lignin ratio [17–19].

Cellulose is the largest fraction and constitutes about 38–50% by weight of lignocellulosic biomass. It is a polymer of glucose, consisting of linear chains of (1,4)-D-glucopyranose units with an average molecular weight of around 100,000. In contrast to other glucan polymers, such as starch, the repeating unit of cellulose is not glucose but rather cellobiose, a disaccharide [19,20]. Globally, about 7.5×10^{10} tonnes of cellulose are annually synthesized through photosynthetic processes [20]. Found primarily in plant cell walls, cellulose is embedded in a hetero-matrix composed of hemicellulose and lignin. Hemicellulose, the second largest constituent of lignocellulosic biomass, is a polymer of 5-carbon mainly xylose, and a 6-carbon monosaccharide. It represents approximately 20–40% of the material by weight of lignocellulosic biomass.

The third major constituent of lignocellulosic biomass, lignin, is regarded as a group of amorphous, high molecular-weight, chemically-related compounds. It constitutes about 15–25% of the composition of lignocellulosic biomass. The building blocks of lignin are believed to be a three-carbon chain attached to rings of six-carbon atoms called phenyl-propane. Structurally, the polymer of softwood lignin is different from that of hardwood [20]. Whereas, softwood lignin is composed mainly of coniferyl alcohol derivatives, with a small component based on coumaryl alcohol, hardwoods have lignin composed of coniferyl- and sinapyl-based alcohols, with small amounts of coumaryl alcohol derivatives. It is reported that the most suitable biomass which produce the highest biochar yield when pyrolysed have high lignin concentration. These include wood waste, forest residues and nut shells [2,16,21–23].

Table 1
Production of different agricultural crops in Ghana for 2008 and estimated availability of residues [15,21].

Crop	Production ($\times 10^3$ tonnes)	Residue type	Residue-to-product ratio (RPR)	Moisture content (%)	Residue (wet, $\times 10^3$ tonnes)	Residue (dry, $\times 10^3$ tonnes)
Sorghum	350	Stalk	2.62	15	917.00	779.45
Millet	160	Stalk	3	15	480.00	408.00
Rice	242	Straw	1.5	15	363.00	308.55
Sugarcane	145	Bagasse	0.3	75	43.50	10.88
Coconut	316	Shell	0.6	10	189.60	170.64
Oil palm fruits	1900	EFB	0.25	60	4750.00	190.00
Coffee	165	Husk	2.1	15	346.50	294.53
Cocoa	700	Pods, husk	1	15	700.00	595.00
Maize	1100	Stalk	1.5	15	1650.00	1402.50
Total					4821.60	4159.55

Extractives constitute about 5–10% by weight of lignocellulosic biomass, while mineral ash constitutes 1–20% by weight, and are composed of nitrogen (N), phosphorus (P), potassium (K), silicon (Si), calcium (Ca), cadmium (Cd), mercury (Hg) and arsenic (As) [16]. The mineral ash content of lignocellulosic biomass varies widely and plays a significant role in the yield of bio-char. Woody biomass impregnated with Na, K and Ca yielded up to 15% more biochar than the original beech wood [2].

2.1. Agricultural resources in Ghana for biochar production

2.1.1. Agricultural residues

Global annual production of agricultural residues is estimated to be more than 500 million tonnes [18]. Ghana's agricultural sector is characterised by a large number of dispersed small-scale producers, employing manual cultivation techniques, and dependent on rain-fed with little or no purchased inputs [15].

Farming systems vary with the six agro-ecological zones and also according to soils and soil management strategies [10]. Major crop residues generated in the country include straw or stalk of cereals such as rice, maize/corn, sorghum and millet, and cocoa pod husk, while agro-industrial by-products include corn/maize cob, cocoa husk, coconut shell and husk, rice husk, oil seed cake, sugarcane bagasse and oil palm empty fruit bunch (EFB). It is estimated that about 4159×10^3 tonnes of agricultural crop residues were generated in the country in 2008 (Table 1) [15]. Assuming 20% crop residues availability, and an estimated biochar yield of 20%, this quantity of agricultural crop residues could have yielded approximately 166,360 tonnes of biochar in that year.

Cocoa is the dominant cash crop and the single most important export product. Cocoa production occurs in the forested areas and covers approximately 1.75 million ha. Currently, cocoa pod husks are left on the farms to mulch. In comparison with cocoa, coffee plantations in the country cover only a total area of approximately 10,000 ha, and coffee production has been relatively low [15]. Coffee husk generated during the processing of the crop can be utilised as an organic fertiliser or for power generation. Additionally, it could be a potential feedstock for biochar production. Major residues generated from harvesting and processing of maize and sorghum such as maize/corn straw and cob, and sorghum straw are potential biochar feedstock [15]. Also, coconut residues, mainly the husk and shells, oil palm empty fruit bunch (EFB) and sugarcane bagasse could be potential feedstock for biochar production. Traditionally, most of the agricultural residues mentioned generated in the country are scarcely utilised. However, there is currently no reliable information on the proportions of how they are utilised. In practice, not all the agricultural residues can be collected and utilised for either bioenergy or biochar production due to technical constraints, ecosystem functions and other uses. Of all the agricultural crops cultivated in Ghana, maize seems to generate more residues than any other crop. The proximate composition of some agricultural residues available in Ghana is presented in Table 2 [15,21–23].

2.1.2. Others

- Grasses

Grasses are usually utilised either as hay and pasture for livestock feed or for soil conservation. However, some species could be used as feedstock for either biofuel or bio-based chemicals production. In Ghana, there is a large availability of various grass species, including elephant grass (*Pennisetum purpureum*), guinea grass (*Panicum maximum*) and mischanthus (*Miscanthus giganteus*) which could be potential feedstock for biochar production. Grasses have high fiber contents. Miscanthus, for instance, has relatively high yields of 8–15 tonnes/ha dry weight and low moisture content. It also tolerates water and uses a minimum amount of nutrients from the soil [15].

- Algae

There are two categories of algae: macroalgae and microalgae. Macroalgae are the large multi-cellular algae often seen growing in ponds. Microalgae, on the other hand, are tiny, unicellular algae that normally grow in suspension within water-bodies. Algal biomass consists of three main components: carbohydrates, proteins and lipids/natural oils [15]. Various macro-algae such as Chlorophyta, Phaeophyta and Rhodophyta species have been found usually attached to rock surfaces in the inter- and sub-tidal areas in Ghana. Research into the utilisation of algae as feedstock for biochar production could provide environmentally friendly solutions to both global and national threats, like GHG emissions [24].

2.2. Forestry residues

Ghana's forest resources provide a major source of biomass that could contribute considerably to biochar production. Estimates provided by the Food and Agriculture Organisation (FAO) of the United Nations indicate that in 2006 the total forest area covered roughly 5.52 million ha, approximately 24.3% of the total land area [25]. Round wood extraction in 2006 amounted to 1.30 million m^3.

Table 2
Proximate composition of some major agricultural residues generated in Ghana [15,22].

Crop residue	Moisture (%)	Organic matter (%)	Ash (%)
Maize stover	10	85–91	9–15
Sorghum stover	10	96	4
Rice straw	10	75–90	10–25
Cocoa pod husk	75	75–90	10–25
Empty oil palm fruit bunch	56	95	5

Table 3
Production and consumption of woodfuel, industrial round wood, sawn wood and wood-based panels for 2008 [25].

Product	Production ($\times 10^3$ m^3)	Consumption ($\times 10^3$ m^3)
Wood fuel	33,040	33,040
Industrial round wood	1304	1305
Sawn wood	527	317
Wood pulp	0	0
Wood based panels	335	161
Paper and paper board	0	0

Table 4
Sources and types of forestry residues [27].

Source of residue	Type of residue
Forest operations	Branches, twig, stump, low-grade and decayed wood, slashings and sawdust
Sawmilling and planning	Bark, sawdust, trimmings, split wood, planer shavings
Plywood production	Bark, core, sawdust, veneer clippings and waste, panel trim, sander dust
Particleboard production	Bark, screening fines, panel trim, sawdust, sander dust

The total growing stock and biomass in the country's forests were estimated to be 321 million m^3 and 993 million tonnes, respectively [15]. In addition, forest plantations in Ghana covered about 76,000 ha in 2000 [26]. Production and consumption of forest products in the country in 2008 is shown in Table 3. Forestry residues can put into two categories: (i) logging residues (which are generated from logging operations, and (ii) wood processing wastes (industrial-by products generated by wood processing firms during the processing of sawn wood, plywood, etc. (Table 4).

2.2.1. Logging residues

Logging residues include stumps, off-cuts, branches, thinning, twigs and saw dust and are referred to as primary residues (Table 4). According to Parikka [27], less than 66% of the volume of woody biomass is generally removed from the forest for further processing, while the remaining quantity is either left on-site, burnt on-site or utilised as wood fuel. However, a study by Amoah and Becker [28] on commercial logging efficiency in Ghana showed an average logging recovery of 75%. This implies that approximately 25% of the total harvested tree is left in the forest unutilised. While logging residues may appear to be an attractive feedstock for biochar production, they are however widely dispersed. In practice, not all of these residues could be used for either bioenergy or biochar production due to technical constraints and ecosystem functions. For instance, leaving appropriate levels of logging residues in the forest protects soil quality and further eliminates the need for fertilisers [15]. It is estimated that 720,000 m^3, equivalent to 360,000 tonnes of logging residues were generated in Ghana in 2008 [15].

2.2.2. Wood processing wastes

Wood processing wastes such as discarded logs, bark, sawdust, and off-cuts generated through sawmill and plywood mill processing activities are referred to be secondary residues (Tables 4 and 5). Generally, recovery rates of sawmills in Ghana range between 20 and 40% of log throughput, averaging 33.3%. Sawmill residues are among the most promising feedstock for bioenergy production [29–31]. It is estimated that about 256,000 m^3, equivalent to 128,250 tonnes of wood processing wastes were generated by the various sawmills in the country in 2008. The actual quantity of wood waste generated varies with tree species, the type of operation and maintenance of the plant [27]. Clearly, the utilisation of wood processing wastes as feedstock for bioenergy or biochar production could be attractive since they are normally concentrated at the various mills, thus easing their collection.

2.3. Urban wastes and other wastes

Urban wastes which have potential for biochar production can be categorised into municipal solid waste (MSW), industrial wastewater, sewage sludge, livestock and poultry wastes.

2.3.1. Municipal solid waste

Municipal solid waste (MSW) is generated by households, commercial and industrial sectors as a result of the concentration of population and activities in urban areas. It is estimated that between 150 kg and 200 kg per capita of MSW are generated in Ghana annually with the 10 regional capitals, together, generating over 2 millions tonnes per year. In Accra, approximately, 760,000 tonnes of MSW is generated annually, or approximately 2000 t day^{-1} is generated and shows a daily per capita rate and density of 0.40 kg and 0.47 t m^{-3}, respectively [15] and [32]. Generally, the organic matter content of MSW is estimated to be 68%. Generally, MSW in Ghana is unsorted and there is also high cost in their collection. Tertiary wood residues such as wood in household waste and demolition wood are considered as organic waste and included in MSW. Clearly, the high percentage of organic matter in MSW indicates a high potential of MSW in Ghana as feedstock for biochar production (Fig. 1). However, the possible presence of heavy metals in MSW may pose a challenge in its utilisation as biochar feedstock [16]. With the current level of socio-economic development in the country, waste disposal practices in the metropolis and municipalities are gradually being transformed from open-air dumping to centralized approaches such as composting, landfill and incineration. For instance, between 2003 and 2004, four sanitary landfill projects, located in Accra, Kumasi, Sekondi-Takoradi and Tamale were commissioned [15,31–36].

2.3.2. Industrial wastewater and sewage sludge

In Ghana, most of the industries are sited along the coast such as Tema, Accra and Sekondi-Takoradi, and dispose of their wastewa-

Table 5
Proportion of residues generated in selected forest products industries [27].

Industry type	Sawmilling (%)	Plywood manufacturing (%)	Particleboard manufacturing (%)	Integrated operations (%)
Finished product	45–55	40–50	85–90	65–70
Finished product (average)	50	47	90	68
Residues/fuel	43	45	5	24
Chips and particles	34, 15			
Bark	28–21			
Sawdust	16–23			
Slabs and edgings	15–32			
Shavings	5–1			
Other	3–7			
Losses	7	8	5	8
Total	100	100	100	100

Table 6
Livestock population in Ghana, 2001–2008 ($\times 10^3$) [15].

Year	2001	2002	2003	2004	2005	2006	2007	2008
Cattle	1315	1330	1344	1365	1385	1406	1427	1427
Goats	3199	3230	3560	3595	3632	3668	3704	3704
Pigs	312	310	303	300	305	229	239	239
Sheep	2771	2922	3015	3112	3211	3314	3420	3420
Poultry	22,032	24,251	26,395	29,500	30,000	30,500	31,000	31,000

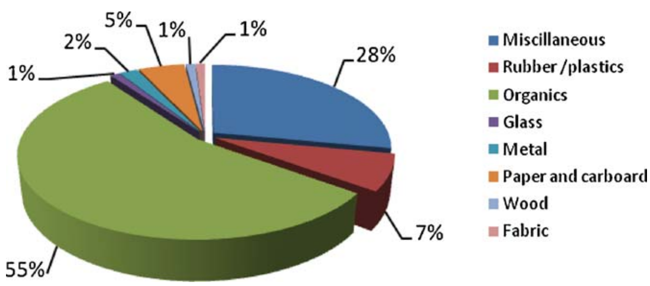

Fig. 1. Composition of household waste in Kumasi [15,33].

ters directly into the sea. Thus, only a few industries and abattoirs carry out some primary industrial wastewater treatment [15]. While sewage sludge can be a feedstock for biochar production, the nature of this resource in Ghana makes it extremely unlikely to be considered as such. Moreover, reliable information on the availability of wastewater or sewage sludge in the country is difficult to access.

2.3.3. Livestock and poultry wastes

Cattle, pig, sheep and poultry are the most domesticated livestock in Ghana. Poultry and livestock population from 2001 to 2008 is shown in Table 6 [15]. Poultry litter, a mixture of bedding, manure, feathers and spilled feed, has an ash content ranging from 15 to 20% [16]. Generally, the quantity of livestock manure produced depends on the amount and quality of the fodder or feed, together with the live weight of the animal. It is estimated that total cattle wet and dry manure produced in the country in 2008 were 22.8 million and 2.9 million tonnes, respectively [15]. If carefully managed and exploited, livestock and poultry wastes could be an important biomass resource for heating, power generation and biochar and biogas production.

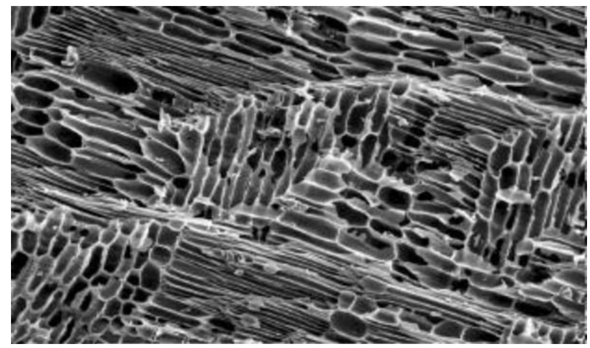

Fig. 3. Biochar structure [38].

3. Biochar production technologies

Thermochemical processes for biomass conversion into biofuels and other bio-based products include pyrolysis, carbonisation and gasification [37] and [38]. A summary of biomass conversion processes is presented in Fig. 2 [39]. Biochar is a solid product of thermochemical conversion of biomass carried out at temperatures above 300 °C in the absence of oxygen, known as pyrolysis. Biochar is not a pure carbon, but rather, it consists of carbon (C), hydrogen (H), oxygen (O), nitrogen (N), sulphur (S) and ash (Fig. 3). Its structure reflects the morphology of the feedstock [38].

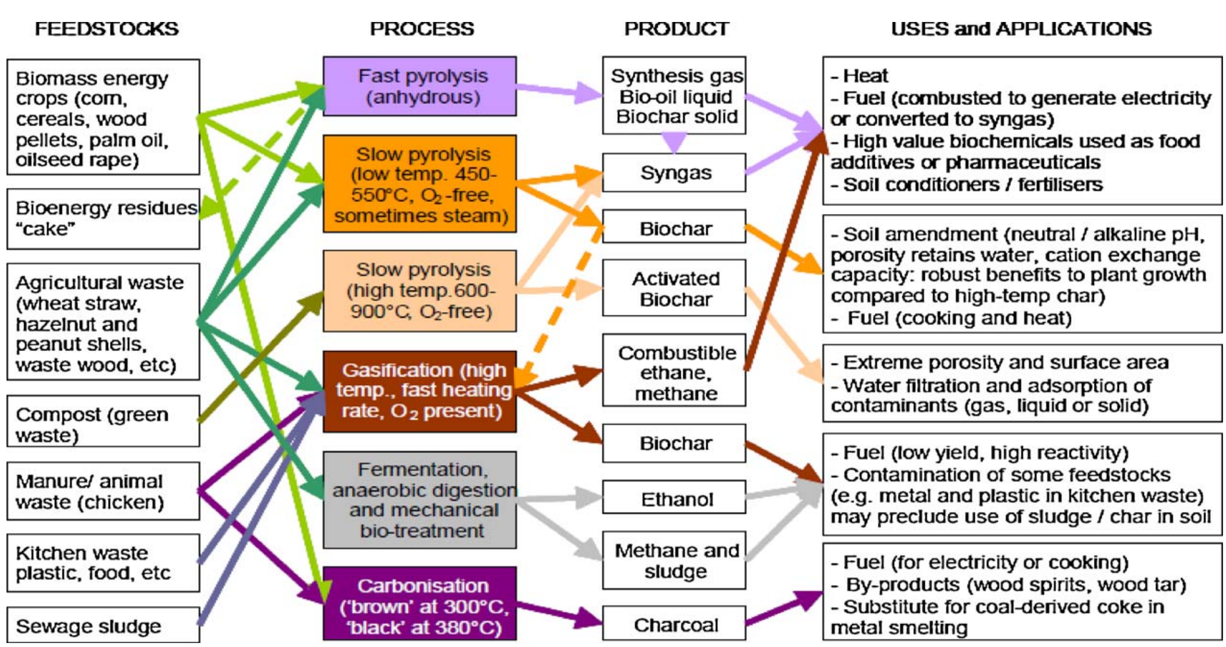

Fig. 2. Summary of biomass conversion processes in relation to their common feedstocks, typical products, and the applications and uses of these products [39].

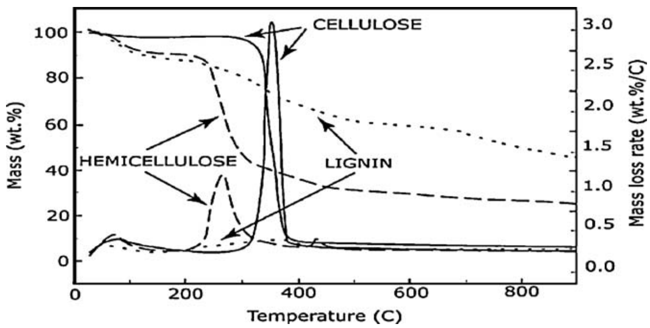

Fig. 4. Thermogravimetric analysis of the pyrolysis of plant components [39].

Pyrolysis is always the first step in combustion and gasification. During pyrolysis, the polymeric building blocks of biomass, namely cellulose, hemicellulose and lignin undergo various processes such as cross-linking, depolymerisation and fragmentation at various temperatures (Fig. 4). The primary products of biomass pyrolysis are usually referred to as condensable (tars) and non-condensable volatiles, and char. The condensable volatiles are often classified as liquids (bio-oil), while the non-condensable volatiles are gases mainly carbon monoxide (CO), carbon dioxide (CO_2), hydrogen (H_2) and C_1–C_2 hydrocarbons [15,38]. The pyrolysis product yields depend on the type, nature and composition of the feedstock, particularly the lignin and ash contents, and process conditions such as temperature, pressure, vapour residence time, heating rates, particle size and heat integration [38–48]. Similarly, the composition, quality and characteristics of biochar such as density, particle size distribution, ash content, moisture content and pH depend on the type, nature and origin of the feedstock, together with pyrolysis reaction conditions [44]. Wood-based biochar, for instance, is reported to be coarse and highly resistant with carbon content up to 80%. Demirbas [49] as cited in Verheijen et al. [1] reports that biomass with high lignin content (e.g. olive husks) produces high biochar yields as a result of the stability of lignin to thermal degradation. In contrast, biochar produced from crop residues (e.g. maize, rye) and manures are generally finer and less robust with low mechanical strength.

An assessment of particle size distribution of biochar produced from sawdust and woodchips under different slow pyrolysis conditions by Downie et al. [5] showed that particle size generally decreased as the pyrolysis temperature increased within the 450–700 °C range. The ash content of the feedstock varies widely and influences the yield of biochar [49,65]. Amonette and Joseph [65] reported that during pyrolysis of biomass, potassium (K), chlorine (Cl) and nitrogen (N) vaporize at relatively low temperatures, while calcium (Ca), magnesium (Mg), phosphorus (P) and sulphur (S) due to increased stability, vaporise at considerably high temperatures. Slow biomass pyrolysis is reported to result in high quantities of K, Cl, Si, Mg, P and S in biochar and biochar yield. Generally, woody feedstock produces biochar which contains low proportions (<1% by weight) of ash, whereas biomass with high mineral content such as grass, grain husks and straw residues produce biochar with high ash contents [49]. These feedstocks may contain ash content up to 24%, or even 41% by weight, such as rice husk and rice hulls, respectively. Animal manure (such as chicken litter) biochar is reported to contain about 45% by weight as ash. Antal and Gronli [45] reported that higher moisture content increases both the cost of production and transportation of biochar. The pH of the biochar is also strongly dependent on pyrolysis conditions and, therefore, varies slightly between the various products, but is typically >7 [14,39].

Based on pyrolysis conditions, pyrolysis can be classified into three basic groups, namely slow, intermediate and fast pyrolysis (Table 7) [38–41]. Energy required to drive the process can be supplied either: (i) directly as the heat of reaction, (ii) directly by flue gases from combustion of by-products and/or feedstock, (iii) indirectly by flue gases through the reactor wall, or (iv) indirectly by heat carrier other than flue gases (e.g., sand, metal spheres, etc.).

In the slow pyrolysis, the process conditions are long vapour residence times more than around 10 s, reactor temperatures between 450 and 650 °C, reactor operating at atmospheric pressure and very low heating rates which range from 0.01 to 2.0 °C s^{-1} [39]. These conditions result in increased cracking reactions that reduce the liquid organic yield and consequently increase the biochar yield. The slow speed of the process, in particular, promotes extensive secondary reactions within the biomass particles and also in the gas and vapour phases, leading to condensation [39]. Higher concentration of pyrolysis vapour and extended vapour/solid contact, on the other hand, promote the formation of coke by secondary reactions. A schematic of biomass slow pyrolysis facility for the production of biochar is represented in Fig. 5.

As can be seen from Table 7, slow pyrolysis and intermediate pyrolysis both result in higher biochar yields, while fast pyrolysis gives higher liquid yields. Thus, to optimize the production of biochar, slow pyrolysis and intermediate pyrolysis seem to be the most appropriate technology choice. Pyrolysis conditions which favour high biochar yields are: (i) high lignin, ash and nitrogen contents in the biomass, (ii) low pyrolysis temperature (<400 °C), (iii) high process pressure, (iv) long vapour residence time, (v) extended vapour/solid contact, (vi) low heating rate, (vii) large biomass particle size, and (viii) optimised heat integration [38,43,47–51]. Production of biochar/charcoal can be categorised into batch, continuous and novel processes (Table 8).

Table 7
Typical product yields (dry wood basis) obtained by different modes of pyrolysis of wood [1,14].

Mode	Condition	Liquid (bio-oil)	Solid (biochar)	Gas (Syngas)
Fast pyrolysis	Moderate temperature (~500 °C) Short vapour residence time (<2 s)	75% (25% water)	12%	13%
Intermediate pyrolysis	Low-moderate temperature Moderate hot vapour residence time	50% (50% water)	25%	25%
Slow pyrolysis	Low-moderate temperature Long residence time	30% (70% water)	35%	35%
Gasification	High temperature (>800 °C) Long vapour residence time	5% tar (55 water)	10%	85%

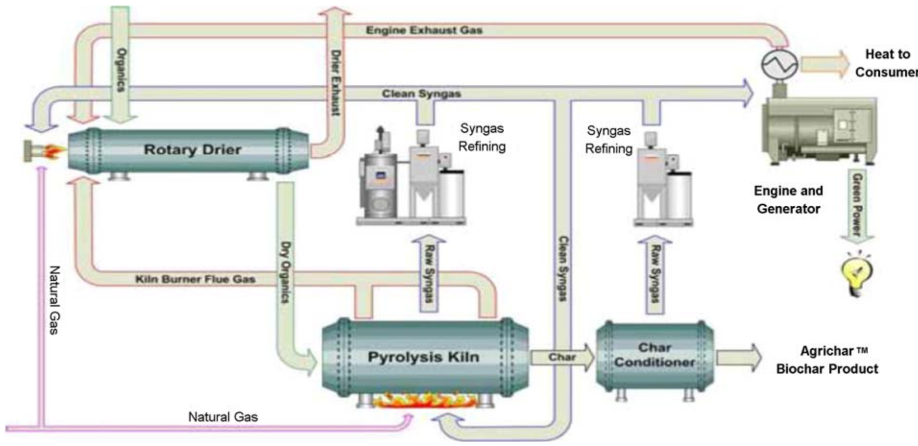

Fig. 5. Illustrative slow pyrolysis process [39] and [50].

Table 8
Biochar production [38,43].

Process type	Reactor type	Biochar yield
Batch process	Earth pits and mounds	>10%
	Brick, concrete and metal kilns	20–25%
	Retorts	30%
Continuous processes	Retort (Lambiotte)	30–35%
	Multiple hearth reactors	25–30%
	Screw type reactor (Pro-Natura)	25–30%
Novel processes	Flash carbonisation	40–50%

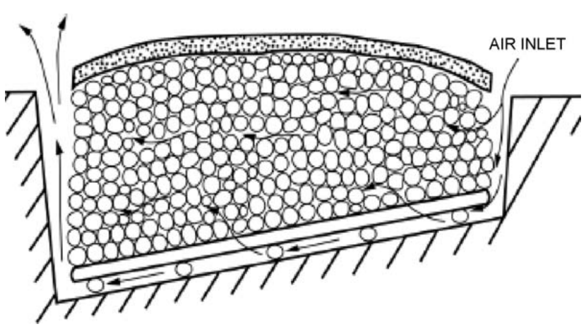

Fig. 6. Pit kiln [40,53].

3.1. Batch processes for biochar production

Traditional charcoal making is carried out using batch processes which include pits, earth mound, brick and metal kilns (Figs. 6 and 7). These processes are based on a simple technology and are also cheap to construct [38,40]. However, they are inefficient in operation leading to low yields coupled with no heat recovery and significant feedstock burn off (Table 8). In Ghana, charcoal is traditionally produced using the earth mound method. In this process, the earth acts as a shield against oxygen by insulating the carbonizing wood against excessive loss of heat. Thermal decomposition of the wood commences when it is raised to a temperature of about 300 °C. The pyrolysis process, once started, continues by itself and gives off considerable heat with a maximum temperature of approximately 500 °C for high efficiency and product quality [52]. Charcoal yields on dry weight basis for different kinds of batch process kilns are shown in Table 8. The yield (η_{fc}) is calcluated according to: $\eta_{fc} = (m_{char}/m_{bio}) \times 100$, where m_{char} = dry mass of charcoal from the kiln and m_{bio} = dry mass of biomass loaded into the kiln [40,53].

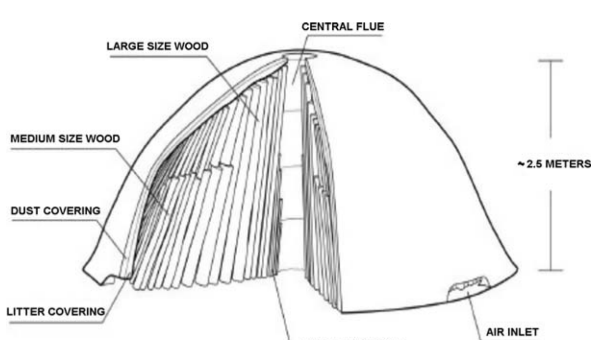

Fig. 7. Mound kiln [40,53].

3.2. Continuous processes for biochar production

Technologies currently available for biochar production include drum type pyrolysers, screw type pyrolysers and rotary kilns. These technologies are based on continuous processes and result in higher biochar yields compared to batch processes [5,14,38,40,49–51]. Each of these reactors has distinct advantages and disadvantages associated with their use (Table 9).

- Drum pyrolysers

In drum pyrolysers, the biomass is moved through an externally heated, horizontal cylindrical shell by the action of paddles before it enters the drum. This assures good biochar and gas quality [40]. No air or oxygen is intentionally admitted, although some enters in the void between feedstocks particles. The gas particles are burned in a firebox below the drum to heat the biomass to pyrolysis temperature. The process is characterised as slow pyrolysis because it takes several minutes for the biomass to travel through the drum, although the time is short compared to traditional batch combustion [40]. The paddle drum pyrolyzer, developed by BEST Energies, Australia (Fig. 8) is an example of continuous pyrolysis systems based on drum reactors which have been widely employed for biochar production [40].

- Screw type pyrolysers

In screw type pyrolysers, the biomass is moved through a tubular reactor by the action of a rotating screw. Screw type pyrolysers may be either externally heated or use a heat carrier such as sand to heat the biomass as it is transported through the tube. These pyrolysers are an attractive option due to their potential to be operated

Table 9
Comparison of various types of reactors for biochar production [38].

Process type	Reactor type	Examples of equipment manufacturers	Advantages	Disadvantages
Batch processes	Earth pits and mounds Brick, concrete and double metal kilns Retorts		Simple technology, cheap and portable.	Inefficient leading to low yield; no heat recovery thus significant feedstock burn off; release of pyrolysis gas and vapours to atmosphere resulting in environmental pollution.
Continuous processes	Retort Multiple hearth reactors	Lambiotte retort		
	Screw type pyrolysers	Pyro-7 by Pro-Natura; Biofuel Energy Systems Ltd.	Higher yields; feedstock flexibility; heat integration; possible co-generation of char and energy; easy to operate, relatively proven technology; combined char and energy generation; available as either portable or stationary unit (depending on size).	More complex systems; more expensive than batch processes. No usable by-products.
	Paddle drum type reactors	BEST Energies, Australia	Relatively proven technology; feedstock flexibility; combined char and energy generation; available as either portable or stationary unit (depending on size); higher yields, heat integration and possible co-generation of char and energy.	More complex systems; more expensive than batch processes.

Fig. 8. The BEST Energies slow pyrolysis reactor [50].

at relatively small scales using of a variety of feedstock, coupled with high yields of biochar. It is also the possible to integrate heat and energy generation with the production of biochar in these systems. Pyro-6 and Pyro-7 manufactured by Pro-Natura International are examples of pyrolysers based on the screw type (Fig. 9). These pyrolyzers have been used recently to convert biomass into bio-oil and biochar [40,50,51]. According to the manufacturers, several units of Pyro-6 have been installed in various parts of Africa for biochar production using different types of lignocellulosic biomass such as agricultural crop residues and forestry residues as feedstock.

Fig. 9. Continuous flow screw type pyrolyser manufactured by Pro-Natura [38,51].

- Rotary kilns

Rotary kiln systems may be classified as indirect, direct and drum kilns depending on the heat source which may be direct or indirect using electricity with capacities which may be up to 1000 kg h^{-1}. These kiln systems are available in different sizes such as medium-size and large with kiln lengths ranging from 4 to 12 m and internal diameter ranging from 0.3 to 1 m. Temperature range within these rotary kilns may be 150–1500 °C. Examples of rotary kiln pyrolysis reactors for biochar production are those produced by Lambiotte (e.g. Lambiotte retort; Fig. 10) and 3R Agrocarbon (Fig. 11). The largest commercial slow pyrolysis plant (MTK, Japan) processes 100 t of biomass per day in a rotary kiln [1,23].

Fig. 10. Lambiotte retort [38].

Fig. 11. Rotary pyrolysis reactor manufactured by 3R Agrocarbon.

4. Potential benefits of biochar application in soils

The application of biochar in soils is based on its properties such as: (i) agricultural value from enhanced soils nutrient retention and water holding capacity, (ii) permanent carbon sequestration, and (iii) reduced GHG emissions, particularly nitrous oxide (N_2O) and methane (CH_4) release [2,40,53–58]. Farmers will be motivated to apply biochar on their farms if these benefits can be demonstrated explicitly. There are various methods for the application of biochar. These include mixing with fertiliser and seed, applying through no till systems, uniform soil mixing, deep banding with plow, top-dressed, hoeing into the ground, applying compost and char on raised beds, and spreading around farms to capture run off. However, the type of application of biochar in soil depends on the farming system, available machinery and labour. The effectiveness of biochar application, however, depends on the method of application [14,53,58,59]. In deep banding applications, biochar is applied beneath the soil surface to a depth which ranges from 0.1 to 0.2 m. According to De Gryze et al. [14], apart from eliminating dust, this method of biochar application in soil also creates both good soil–biochar and plant–biochar contact. In top-dressed biochar applications, biochar is added to the soil surface.

4.1. Agronomic benefits

4.1.1. Soil quality and fertility improvement

The addition of biochar to agricultural soils is receiving considerable interest due to the agronomic benefits it may provide [3]. Biochar can act as a soil conditioner by improving the physical and biological properties of soils such as water holding capacity and soil nutrients retention, and also enhancing plant growth [39] as cited in De Gryze et al. [14]. Several authors [38,41,47,59–77], also report that biochar has the potential to: (i) increase soil pH, (ii) decrease aluminium toxicity, (iii) decrease soil tensile strength, (iv) improve soil conditions for earthworm populations, and (v) improve fertiliser use efficiency. The combined application of biochar and inorganic fertilizer has the potential to increase crop productivity, thus providing additional incomes, and reducing the quantity of inorganic fertilizer use and importation [3,14]. Biochar additions to hard setting soils in Australia, for instance, reduced tensile strength and further improved plant growth [65,67]. Steiner et al. [55] report that application rate of 5 tonnes of biochar per ha decreased fertilizer needs by 7%. According to Gaunt and Lehmann [46], lessons learned from terra preta suggest that biochar can have carbon storage permanence in the soil for many hundreds to thousands of years. Biochar as a method of carbon management is widely scalable in size and flexible across soil type and usage, making biochar deployable worldwide. Charcoal was first used as soil amendment in the Amazon Basin of South America over 2500 years ago. The terra preta de Indio (dark soil) are believed to have been created from the deposition of nutrient-rich materials and charcoal within the zone of habitation and associated garden areas resulting from human activities either anthropic (unintentionally formed) or anthropogenic (intentionally formed) [53–55]. Although, they occur in small patches averaging 20 ha, sites as large as 350 ha have also been reported, and have shown how over millennia the use of biochar has enhanced soil fertility [56]. These soils still contain high carbon contents, despite their age of 500–2500 years and intensive cultivation. There are also available in them significantly higher levels of soil organic matter (SOM) and nutrients than in the surrounding Oxisols. Crops are reported to grow about three times faster on these soils than on surrounding land [39]. Similar soils have been identified in other parts of the Amazon region such as Ecuador and Peru, and also in places in West Africa such as Benin and Liberia, and the savannah of South Africa [39,71]. It is this observation coupled with the search for carbon sequestration techniques for climate change mitigation that has led to the recent interest in biochar to enhance agricultural productivity and sustainability [56]. The terra preta are reported to show more favourable pH conditions (pH 5.0–6.4) than adjacent soils with an absence of biochar (pH 3.9–4.6) [60]. Similar increases in soil pH have been found on active or historical charcoal-making areas in Ghana, Mexico and Pennsylvania [72,73].

Biochar can be used by farmers to control the pH of soil and also to reduce lime applications [74]. Rodriguez et al. [75] used biochar produced from sugarcane bagasse to increase the pH of soil from 4.0–4.5 to 6.0–6.5 in a maize trial in Colombia. The pH increase in sandy and loamy soils has been reported to be larger than in clayey soils [14]. In a study on the effects of charcoal production on soil physical and hydrological properties in Ghana by Oguntunde et al. [76] reported that the saturated hydraulic conductivity of soils under charcoal kilns increased significantly. When mixed with organic matter, biochar can result in enhanced retention of soil water as a result of its pore structure which contributes to nutrient retention because of its ability to trap nutrient-rich water within the pores [14,76,77]. Results of the effects of heating and charcoal residues on maize yield in Ghana investigated by Oguntunde and his co-workers [72] showed a significant increase in soil pH, electrical conductivity and exchangeable Ca, Mg, K, Na and P in the soil at the charcoal site soils or kiln sites compared to the adjacent soils.

In Ghana, farming systems vary with the agro-ecological zones and their respective soils, and also soil management strategies [10]. Partial burning or rotational slash and char system practised in some agricultural margins of the country is reported to typically double crop yields, and further reduce encroachment on forest areas [6]. Generally, most of the soils in the country are developed on extremely weathered parent materials, with alluvial soils (Fluvisols) and eroded soils (Leptosols) common to all the agro-ecological zones. They are further plagued with inherent or human induced infertility [13]. An overview of the nature and extent of degradation of solids in the country is shown in Table 10 [10].

Biochar-based soil management strategies in Ghana are new and have not been evaluated in the context of the country's agricultural system. Only a few farmers in the country have applied biochar to agricultural soils. Biochar incorporation in soils has mostly been carried out within the context of research and testing. However, population pressure, coupled with dwindling land availability, declining soil fertility and issues related to energy security and climate change adaptation provide a strong basis for the application of biochar in the country's farming systems. Thus, biochar application could provide a new technology for both soil fertility and crop productivity improvement, with potential positive and quantifiable environmental benefits, such as carbon trading [6] and [57].

Table 10
Comparison of the ecological zones of Ghana [63].

Ecological zone	Climate	Soil characteristics	Cropping systems	Detrimental practices
Sudan savannah	Mono-modal rainfall 1000 mm/year, mean daily temperature 34 °C	Light textured Luvisols, Lithosol and Fluvisols, highly erodible, low water holding capacity, organic matter, CEC and NPK.	Sorghum, millet and groundnut.	Annual bush fires, removal of crops residues, post-harvest, uncontrolled and over-grazing, cultivating down-slope and inadequate use of fertilisers.
Guinea savannah	Mono-modal rainfall 1100 mm peaking in August–September, mean daytime temp 34 °C	Luvisols and Gleysol, the latter of which are poorly drained but less erodible, similar fertility characteristics to the Sudan savannah zone, and have an iron pan in their profiles.	Sorghum, cowpeas, maize, yam and cassava.	In addition to the above, removal of woody species for fuel and charcoals burning and the intensive shifting cultivation of yam also reduces soil fertility.
Forest savannah transition	Bi-modal rainfall (April–August and September–November) 1300 mm, mean daytime temp 33 °C	Mostly moderately sandy, deep Lixsols and Cambisols, poor to good drainage, prone to erosion; have low water holding capacity, organic matter, CEC and NPK.	Maize, cowpea, groundnut, cassava and yam.	Bush fires, continuous maize cropping without fertiliser inputs, low organic manure input, and poor grazing practices and removal of crop residues.
Semi deciduous rainforest	Bimodal 1500 mm mean daytime temp 31 °C	Moderately well drained Acrisols, Nitisols and Gleysols, low organic matter content when cropped, NPK deficiency, subsoil acidity low CEC and erodability, reasonable water holding capacity.	Maize, cassava, plantain and cocoyam.	Short fallow periods, slash and burn, removal of weeds from the field; cultivation of slopes without soil conservation measures, removal of woody species for timber and fuel and inadequate fertiliser use.
High rainforest	Bi-modal 2200 mm mean daytime temp 29 °C	Highly weathered Ferrasols and Acrisol; light textured, acidic and heavily leached, high Al ion concentrations leading to low fertility and P availability; low CEC and organic matter.	Maize, cassava, plantain and cocoyam.	Same reasons as given above.
Coastal savannah	Bi-modally distributed, though later rainy season is not sufficiently reliable for cropping	Heavy poorly drained. Vertisols and Regisols to deep well-drained Greysol; may be difficult to cultivate with hand tools but higher in organic C and N; all have low P, CEC and plant soil water availability.	Maize vegetables and irrigated rice.	Bush burning, poor grazing practice, deforestation for charcoal and removal of stones on steep ground.

4.1.2. Crop productivity

Several workers have reported that biochar applications to soils have shown positive responses for net primary crop production, grain yield and dry matter [64,66,68,77]. The impact of biochar application is seen most in highly degraded acidic or nutrient-depleted soils. Low charcoal additions (0.5 t ha^{-1}) have shown marked impact on various plant species, whereas higher rates seemed to inhibit plant growth [78,79]. Crop yields, particularly on tropical soils can be increased if biochar is applied in combination with inorganic or organic fertilizers [56,79,80]. Oguntunde and his co-workers [72] investigating the effect of heating and charcoal residue on maize yield in Ghana reported that grain and biomass yield of maize increased by 91% and 44%, respectively on charcoal site soils compared to adjacent field soils. Table 11 shows crop yield responses as related to relevant biochar properties.

4.2. Environmental benefits of biochar application in soils

4.2.1. Carbon sequestration using biochar

Carbon sequestration is the capture and subsequent storage of carbon to prevent it from being released to the atmosphere. Large amounts of carbon in biochar may be sequestered in the soil for long periods estimated to be hundreds to thousands of years [2,57,79,80]. Marris [81] suggests that a 250-ha farm could sequester approximately 1900 tonnes of CO_2 per year as cited by Bracmort [57]. While biochar eventually mineralises in soils, a fraction of it remains in a very stable form with a ^{14}C age greater than that of the oldest soil organic matter (SOM) fractions [59]. This property of biochar provides it the potential to be a major carbon sink. Compared with other terrestrial sequestration strategies, such as afforestation or re-forestation, carbon sequestration in biochar increases its storage time [39,79]. Furthermore, it is relatively simple to verify the benefits that can be derived from the application of biochar as soil amendment. It is also easy to monitor carbon sequestration as a climate change mitigation measure for national carbon accounting [2,6,7,56,82]. This can be done by using the income generated and the quantity of carbon that has been sequestered [82].

4.2.2. Greenhouse gas emission reduction

Apart from carbon sequestration, there are other environmental benefits that can be derived from the application of biochar in soils which include reduction in the emission of non-CO_2 GHGs by soils. According to Bracmort [57], cropland soils and grazing lands are a major agricultural source of N_2O emission. When applied to the soil, biochar can lower GHG emissions of cropland soils by substantially reducing the release of N_2O [4]. Reduction of N_2O and CH_4 emission as a result of biochar application is seen to attract considerable attention due to the much higher global warming potentials of these gases compared to CO_2 [54]. Rondon et al. [70] reported a 50% reduction in N_2O emissions from soybean plots and almost complete suppression of CH_4 emissions from biochar amended acidic soils in the Eastern Colombian Plains. Yanai et al. [69], however, reported an 85% reduction in N_2O emission from re-wetted soils containing 10% biochar, compared to soils without biochar as cited in Steiner [54]. Spokas et al. [68] also found a significant reduction in N_2O emission in agricultural soils in Minnesota, while Sohi et al. [39] found an emission suppression of only 15%.

Table 11
Crop yield responses as related to relevant biochar properties [66,81].

Feedstock for biochar and rate of application	Crops/plants	Responses	Reasons
Unknown wood (0.5 t ha^{-1})	Soybean	Biomass increased by 51%	Water holding capacity
Bamboo (unknown rate)	Tea tree	Height and volume increase of 20% and 40%, respectively	Retained fertiliser, maintained pH
Bark of *Acacia mangium*	Maize, cowpeas peanuts 2 sites	Biomass increase of 200%	Increase in P and N availability and reduction of exchangeable Al^{3+}
Secondary forest wood (11 t ha^{-1})	Rice and sorghum	Little response with biochar alone. Yield increase of 880% using a combination of biochar and fertiliser	Not stated
Rice husk (10 t ha^{-1})	Maize, soybean	Yield increase of 10–40%	Not clearly understood
Green waste (10–100 t ha^{-1})		No positive effect with biochar with application rates up to 100 t ha^{-1}. Biomass increase of 266% with added fertiliser	Indirect effect of improving hard setting soil
Paper mill sludge (10 t ha^{-1})	Wheat	Increase in wheat heath of 30–40% in acid soil	Mainly liming value

Various workers have reported reduction of ammonium losses on application of biochar to soils. In a pot trial with rice plants, Lehmann et al. [61] found that the addition of fresh biochar reduced ammonium losses by 10%. Biochar increased N retention when combined with ammonium sulphate (NH_4SO_4) fertilizer on highly weathered soils with extremely low cation exchange capacity (CEC) [55], and increased plant uptake of fertilizer N on biochar plots [14]. Thus, biochar decreases the possibility of nutrient leaching in soils and enhances nutrient cycling, resulting in positive impacts on crop yields [14]. Liang et al. [60] and Cunha et al. [71] found higher CEC in terra preta soils compared to adjoining soils in Brazil. Biochar additions in a laboratory trial also increased sorption of two common herbicides [14].

5. Conclusion

Biochar production and application in soils has a very promising potential for the development of sustainable agricultural systems in Ghana, and also for global climate change mitigation. The review shows that there is significant availability of biomass resources in the country as potential feedstock for biochar production. However, to promote the application of biochar as a soil amendment, and also as a climate change abatement option, research, development and demonstration on biochar production and application outlined below seem to be very vital. First, a baseline study comprising compilation and analysis of data on biomass resources, including types and ease of collection in Ghana needs be conducted. Second, a review of current biomass utilisation and thermochemical conversion technologies, particularly slow pyrolysis also has to be carried out. It is also relevant to create awareness among the various biochar stakeholders such as farmers, agricultural extension officers, research scientists and fertilizer wholesalers, and to build their capacities in biochar production and application technologies, project monitoring and evaluation, design and testing through the development and implementation of training programmes.

Since there are both agronomic and environmental benefits that could be derived from the production and application of biochar in soil, implementation of agricultural schemes involving the application of biochar should first be critically evaluated in the form of a pilot or demonstration project. This could then be transformed into large-scale schemes throughout the country. Participatory approach could be adopted in conducting on-farm trials using the biochar that would be produced. Finally, a business plan for national scale-up biochar production and application project could be prepared based on available carbon finance opportunities in the country.

Acknowledgements

The research is supported by the Leverhulme-Royal Society African Award and the UK Engineering and Physical Sciences Research Council (EPSRC) grant: EP/G034281/1.

References

[1] Verheijen F, Jeffery S, Bastos AC, van der Velde M, Diafas I. Biochar application to soils: a critical scientific review of effects on soil properties, processes and functions. European Commission; 2010, http://eusoils.jrc.ec.europa.eu/esdb_archive/eusoils_docs/other/EUR24099.pdf.
[2] Lehmann J, Gaunt J, Rondon M. Biochar sequestration in terrestrial ecosystems – a review. Mitigation and Adaptation Strategies for Global Change 2006;11:403–27.
[3] Quayle WC. Biochar potential for soil improvement and soil fertility. In: IREC Farmers Newsletter, Large Area No. 182: Autumn; 2010, www.irec.org.au/farmer./Biochar%20_a%20means%20of%20storing%20carbon.pdf.
[4] Lehmann J. Bio-energy in the black. Frontiers in Ecology and the Environment 2007;5(7):381–7.
[5] Downie A, Crosky A, Munroe P. Physical properties of biochar. In: Lehmann J, Joseph S, editors. Biochar for environmental management: science and technology. London, UK: Earthscan; 2009.
[6] Yeboah E, Ofori P, Quansah GW, Dugan E, Sohi S. Improving soil productivity through biochar amendments to soils. African Journal of Environmental Science and Technology 2009;3(2):34–41.
[7] Yeboah E, Covell P. Biochar – prospects for Africa. In: Paper delivered at Katoomba XV – Ghana, integrated solutions: water, biodiversity and terrestrial carbon in West Africa. 2009., http://www.katoombagroup.org/event_details.php.
[8] Dovanan G, Casey F. Soil fertility management in sub-Sahara Africa. In: World Bank technical paper no. 480; 1998.
[9] Biggelaar C, Lal R, Wiebe K, Breneman V. The global impact of soil erosion on productivity. Advances in Agronomy 2004;18:1–95.
[10] Oppong-Anane K. Country pasture/forage profiles Ghana. Soils and Topography, http://www.fao.org/ag/AGP/agpc/doc/Counprof/Ghana/Ghana.htm.
[11] Quaye K, Hall CAS, Luzady VA. Agricultural land use efficiency and food crop production in Ghana. Environment and Sustainable Development 2010, doi:10.1007/s10668-010-9234.
[12] Mensah-Bonsu K, Yerfi F, Kwakye PK. Soil management in Ghana. Final technical report for the World Bank. Washington, DC, USA; 1996.
[13] MoFA. National soil fertility management action plan. Ministry of Food and Agriculture of the Government of Ghana; 1998, http://epa.gov.gh/ghanalex/policies/NAP.pdf.
[14] De Gryze S, Cullen M, Durschinger L, Lehmann J, Bluhm D, Six J, et al. Evaluation of opportunities for generating carbon offsets from soil sequestration of biochar. In: An issues paper commissioned by the Climate Action Reserve, final version, April; 2010, http://www.terraglobalcapital.com/press/Soil_Sequestration_Biochar_Issue_Paper1.pdf.
[15] Duku MH, Gu S, Hagan EB. A comprehensive review of biomass and biofuels potential in Ghana. Renewable & Sustainable Energy Reviews 2011;15(1):404–41.
[16] Agblevor FA. Thermochemical conversion of biomass to biofuels. In: ICS-UNIDO Biofuels workshop. 2007., www.ics.trieste.it/media/138286/df5115.pdf.
[17] McHenry MP. Agriculture biochar production, renewable energy generation and farm sequestration in Western Australia: certainty, uncertainty and risk. Agriculture, Ecosystems and Environment 2009;129:1–7.
[18] Sánchez C. Lignocellulosic residues: biodegradation and bioconversion by fungi. Biotechnology Advances 2009;27:185–94.

[19] Mohan, Pittman Jr CU, Steele PH. Pyrolysis of wood/biomass for bio-oil: a critical review. Energy and Fuels 2006;20:848–9.

[20] Monserrate E, Leschine SB, Canale-Parola E. *Clostridium hungatei* sp., a mesophillic, N_2-fixing cellulolytic bacterium isolated from soil. International Journal of Systematics, Evolution and Microbiology 2001;51:123–32.

[21] FAOSTAT. Crop production Ghana. Rome, Italy: Food and Agriculture Organisation of the UN; 2008, http://faostat.fao.org/site/567/default.aspx.

[22] FAO. Utilisation of crop residues in the nutrition of sheep and goats in the humid tropics of West Africa. Food and Agriculture Organisation of the United Nations corporate document repository; 2010, http//:www.fao.org/docrep/004/s8374b/S8374b06.htm.

[23] Collison M, Collison L, Sakrabani R, Tofield B, Wallage Z. Biochar and carbon sequestration: a regional perspective, Norwich, UK: The Low Carbon Innovation Centre, University of East Anglia, a report prepared for East of England Development Agency (EEDA), DA1 Carbon Reduction, Ref. No: 7049; 2009, www.uea.ac.uk/./1.118134!LCIC%20EEDA%20BIOCHAR%20REVIEW%2020-04-09.

[24] Singh J, Gu S. Commercialisation potential of microalgae for biofuels production. Renewable & Sustainable Energy Reviews 2010;14:2596–610.

[25] FAO. State of the world's forests 2009. Rome, Italy: Food and Agriculture Organisation of the UN, www.fao.org/docrep/012/i0680e/i0680e09.pdf.

[26] Zhang D, Owiredu EA. Land tenure, market, and the establishment of forest plantations in Ghana. Forest Policy and Economics 2007;9(6):602–10.

[27] Parikka M. Global biomass fuel resources. Biomass and Bioenergy 2004;27:613–20.

[28] Amoah M, Becker G. Assessment of logging efficiency and development of allometric models for predicting stumpage volume of some commercial tree species in Ghana. International Forestry Review 2009;11(1):1–11, www.bioone.org/doi/pdf/10.1505/ifor.

[29] Atakora S-B, Hagan EB, Brew-Hammond A. Providing power from sawmill residues in Ghana, a case study on Maxwell Owusu Timbers (MOW), www.nrbp.org/papers/039.pdf.

[30] Sekyere D, Okyere PY. The potential of using wood residue for energy generation in Ghana. In: International conference on wood-based bioenergy. 2007., www.itto.int/direct/topics/topics.

[31] Energy Sector Management Assistance Programme, Ghana: sector reform and the pattern of the poor. Energy Use and Supply, ESMAP technical paper 097/06, March 2006, http://www.esmap.org/files/.

[32] Kramer H, Jechimer K, Lengsfeld S, Nartey-Tokolli IB. Determination of major planning data for solid waste management in Accra metropolis. Accra, Ghana: Accra Metropolitan Assembly, Waste Management Department; 1994.

[33] Ketibuah E, Asase M, Yusif S, Mensah MY, Fischer K. Comparative analysis of household waste in the cities of Stuttgart and Kumasi – options for waste recycling and treatment in Kumasi. In: 19th international CODATA conference. 2005., www.codata.org/./Ketibuah-Comparative AnalysisofHouseholdWaste.htm.

[34] Owusu K, Kuitunen M. Municipal solid waste management in the Accra Metropolitan Area, Ghana. The Environmentalist 2003;23(3):211–8.

[35] Fobil JN, Carboo D, Armah AN. Evaluation of municipal solid wastes (MSW) for utilisation in energy production in developing countries. International Journal of Environmental Technology and Management 2005;5(1):76–86.

[36] Anomanyo ED. Integration of municipal solid waste management in Accra (Ghana): bioreactor treatment technology as an integral part of the management process, MSc Thesis. Sweden: Lund University; 2004, http://www.lumes.lu.se/database/alumni/03.04/theses/anomanyo_edward.pdf.

[37] Singh J, Gu S. Biomass conversion to energy in India – a critique. Renewable & Sustainable Energy Reviews 2010;14:2596–610.

[38] Masek O. Biochar production technologies, http://www.geos.ed.ac.uk/sccs/biochar/documents/BiocharLaunch-OMasek.pdf.

[39] Sohi S, Loez-Capel SE, Krull E, Bol R. Biochar's roles in soil and climate change: a review of research needs. CSIRO, land and water science report 05/09, February; 2009. 64 pp., www.ias.ac.in/currsci/10nov2010/1218.pdf.

[40] Brown RC. Biochar Production Technology, Center for Sustainable Environmental Technologies, Department of Mechanical Engineering, Iowa State University. Bioenergy conference; 2009, www.bioeconomyconference.org/./Brown,%20Richard.pdf.

[41] McLaughlin H. Biochar and energy linkages. In: Biochar and energy co-products, Assessment of biochar's benefits for the United States of America, June 2010, U.S.-focused biochar report, www.biochar-us.org/pdf%20files/biochar_report_lowres.pdf.

[42] Yaman S. Pyrolysis of biomass to produce fuels and chemical feedstocks. Energy Conversion and Management 2004;45:651–71, www.bioeconomy-conference.org/./Brown,%20Richard.pdf.

[43] Evans RJ. The relation of pyrolysis processes to charcoal chemical and physical properties. In: Symposium on black carbon in soils and sediments: formation, stabilization, abundance and environmental function. Joint meeting of the Geological Society of America & the Soil Science Society of America, www.biochar-international.org/images/Evans_SSSACharcoal100508-3.pdf.

[44] Zhang Q, Yang Z, Wu W. Role of crop residue management in sustainable agricultural development in the North China Plain. Journal of Sustainable Agriculture 2008;32(1):137–48, http://www.informaworld.com.

[45] Antal MJ, Gronli M. The art, science and technology of charcoal production. Journal of American Chemical Society 2003;42:1619–40.

[46] Gaunt J, Lehmann J. Energy balance and emissions associated with biochar. Sequestration and pyrolysis bioenergy production. Environmental Science & Technology 2008;42:4152–8, http://www.css.cornell.edu/faculty/lehmann/publ/ES%26T%2042,%204152-4158,%202008%20Gaunt.pdf.

[47] Brownsort PA. Review of scope, control and variability. UKBRC working paper 5, December; 2009, www.geos.ed.ac.uk/sccs/biochar/documents/WP5.pdf.

[48] Demirbas A. Carbonisation ranking of selected biomass for charcoal, liquid and gaseous products. Energy Conversion and Management 2001;42: 1229–38.

[49] Demirbas A. Effect of temperature and particle size on biochar yield from pyrolysis of agricultural residues. Journal of Analytical and Applied Pyrolysis 2004;721:243–8.

[50] BEST Energies Inc., http//:www.bestenergies.com/companies/bestpyrolysis.html.

[51] Pro-Natura International, http://www.pronatura.org/archives/200812_Green-Charcoal_en.pdf.

[52] FAO, Food and Agriculture Organisation of the United Nations. Simple technologies for charcoal making. FAO forestry paper 41. Rome: FAO; 1983, www.fao.org/docrepS5328e.

[53] Kammen DM, Lew DJ. Review of technologies for the production and use of charcoal. Renewable and Appropriate Energy Laboratory, Berkeley University, March 1; 2005, http://rael.berkeley.edu/files/2005/Kammen-Lew-Charcoal-2005.pdf.

[54] Steiner C. Biochar in agricultural and forestry applications. In: Biochar from agricultural and forestry residues – a complimentary use of waste biomass, U.S.-focused biochar report: Assessment of biochar's benefits for the United States of America; 2010, www.biochar-us.org/pdf%20files/biochar_report_lowres.pdf.

[55] Steiner C, Glaser B, Teixeira WG, Lehmann J, Blum WEH, Zech W. Nitrogen retention and plant uptake on a highly weathered central Amazonian Ferralsol amended with compost and charcoal. Journal of Plant Nutrition and Soil Science 2008;171:893–9.

[56] Glaser B, Lehmann J, Zech W. Ameliorating physical and chemical properties of highly weathered soils in the tropics with charcoal – a review. Biology and Fertility of Soils 2002;35:219–30.

[57] Bracmort K. Biochar: examination of an emerging concept to mitigate climate change, February 1, 2010. Congressional Research Service, 7-5700, R40186, Congressional Research Service (CRS), Report for congress, prepared for members and committees of congress, www.fas.org/sgp/crs/misc/R40186.pdf.

[58] Joseph S. Bring biochar to the market. In Materials, processes and plant consideration. Materials Science and Engineering, Faculty of Science, The University of New South Wales, www.bioeconomyconference.org/images/Joseph,Stephen.pdf.

[59] Schmidt MWI, Noack AG. Black carbon in soils and sediments: analysis, distribution, implications and current challenges. Global Biogeochemical Cycles 2000;14:777–93.

[60] Liang B, Lehmann J, Solomon D, Kinyangi J, Grossman J, O'Neill B, et al. Black carbon increases cation exchange capacity in soils. Soil Science Society of America Journal 2006;70:1719–30.

[61] Lehmann J, da Silva Jr JP, Steiner C, Nehls T, Zech W, Glaser B. Nutrient availability and leaching in an archaeological Anthrosol and a Ferralsol of the Central Amazon basin: fertilizer, manure and charcoal amendments. Plant and Soil 2003;249:343–57.

[62] Lehmann J, Rondon M. Biochar soil management on highly weathered soils in the humid tropics. In: Uphoff N, editor. Biological approaches to sustainable soil systems. Boca Raton, FL: CRC Press; 2006. p. 517–30.

[63] Stewart TP. The contribution of small ruminants to soil fertility management in the forest and savannah zones of Ghana; 2002, www.bradburystewart.com/./The%20Contribution%20of%20Small%20Ruminants%20to%20S.

[64] Chan Y, Van Zwieten L, Meszaros I, Downie A, Joseph S. Using poultry litter biochars as soil amendments. Australian Journal of Soil Research 2008;46:437–44.

[65] Amonette JE, Joseph S. In Lehmann J, Joseph D, editors. Characteristics of biochar: micro-chemical properties; 2009 [Chapter 3], www.harvestcleanenergy.org/conference/HCE9/./JimAmonette.pdf.

[66] Chan KY, Xu Z. Biochar: nutrient properties and their enhancement. In Lehmann J, Joseph S, editiors. Biochar for environmental management, science and technology. London, UK: Earthscan; 2009. p. 67–84.

[67] Gaskin JW, Speir A, Morris LM, Ogden L, Harris K, Lee D, et al. Potential for pyrolysis char to affect soil moisture and nutrient status of a loamy sand soil. In: Proceedings of the Georgia water resources conference. Athens, GA: University of Georgia; 2007, www.terraglobalcapital.com/./Soil_Sequestration_Biochar_Issue_Paper1.pdf.

[68] Spokas KA, Koskinen WC, Baker JM, Reicosk DC. Impacts of woodchip biochar additions on greenhouse gas production and sorption/degradation of two herbicides in a Minnesota soil. Chemosphere 2009;77:574–81.

[69] Yania Y, Toyota K, Okazaki M. Effects of charcoal addition on N_2O emissions from resulting from rewetting air-dried soil in short-term laboratory experiments. Soil Science and Plant Nutrition 2007;53:181–8.

[70] Rondon M, Ramirez JA, Lehmann J. Charcoal additions reduce net emissions of greenhouse gases to the atmosphere. In Proceedings of the 3rd USDA symposium on greenhouse gases and carbon sequestration; 2005, p. 208.

[71] Cunha TJF, Madari BE, Canellas LP, Ribeiro LP, de Melo Benites V, de Araujo Santos G. Soil organic matter fertility of the anthropogenic dark earths (Terra Preta de Indio) in the Brazilian Amazon basin. Revistas Brasileira de Ciencia de solo 2009;33:85–93.

[72] Oguntunde PG, Fosu M, Ajayi AE, van de Giesen N. Effects of charcoal production on maize yield, chemical properties and texture of soil. Biology Fertility Soils 2004;39:295–9.

[73] Mikan CJ, Abrams MD. Altered forest composition and soil properties of historic charcoal hearths in southeastern Pennsylvania. Canadian Journal of Forest Research 1995;25:687–96.
[74] Rodriguez V, Al-Asmi HS, Esechie HA. Effect of pyroligneous liquid on growth and yield of maize (*Zea mays* L.). Crop Research 2002;24:471–5.
[75] Rodríguez L, Salazar P, Preston TR. Effect of biochar and biodigester effluent on growth of maize in acid soils. Livestock Research for Rural Development 2009;21(7):110, http://www.lrrd.org/lrrd21/7/rodr21110.htm.
[76] Oguntunde PG, Abiodun BJ, Ajayi AE, van de Giesen N. Effects of charcoal production on soil physical properties in Ghana. Journal of Plant Nutrition and Soil Science 2008;171(4):591–6.
[77] Major J, Steiner C, Downie A, Lehmann J. Biochar effects on nutrient leaching. In Lehmann J, Joseph S, editors. Biochar for environmental management: science and technology; 2009. p. 271–87.
[78] Glaser B, Haumaier L, Guggenberger G, Zech W. The terra preta phenomenon: a model for sustainable agriculture in the humid tropics. Naturwissenschaften 2001;88:37–41.
[79] Ogawa M, Okimori Y, Takashi F. Carbon sequestration by carbonisation of biomass and forestation: three case studies. Mitigation and Adaptation Strategies for Global Change 2006;11:421–36.
[80] Woolf D. Biochar as a soil amendment – a review of the environmental implications, January 2008, Swansea University. International Rice Research Institute, Black Soil, Green Rice, Rice Today; April–June 2007.
[81] Marris E. Black is the new green. Nature 2006;442(10):469–624.
[82] Gaunt J, Cowie A. Biochar, greenhouse accounting and emission trading. In: Lehmann J, Joseph S, editors. Biochar for environmental management: science and technology; 2009. p. 317–36.